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THE EFFECT OF STATION RADIO NOISE SOURCES ON TRANSMISSION LINE NOISE LEVELS

J. J. LaForest,* Senior Member IEEE

INTRODUCTION

During the past 15 years, much attention has been given to the determination of transmission-line radio-noise (RI) levels resulting from conductor corona. Excellent results have been obtained using a theoretical approach based on radio-noise power analysis and modal propagation arguments.[1,2,3,4] It is now appropriate to examine the effect of bus-and-station-equipment corona on transmission-line radio-noise levels. Many of the arguments and techniques used in describing the effects of conductor corona on RI levels can be used directly for the case of corona generated in a station. Examination of the question of whether or not station noise is important to line noise levels is particularly timely now because of the large amount of ehv station apparatus being designed and built, and the interest in uprating stations to higher voltage levels than those for which they were designed. Situations where the radio-noise performance of equipment is used as a quality-control index are not considered in this discussion.

This paper will first describe a procedure for calculating line RI levels where the corona effects originate from station equipment and then apply this procedure to two cases with comments on the results thereof.

ANALYSIS AND DISCUSSION

Station Considerations

The initial analysis considers a single noise source on one phase of a typical three-phase station-and-line arrangement. Later, procedures for combining multiple sources, either on the same phase or on all phases, will be discussed. Figure 1 shows a block diagram of the station-and-line impedances with radio-noise generation from a piece of equipment being represented as a constant-current noise generator. The noise current, represented as a spectral-density function,[1] divides into a portion entering the line and a portion entering the station.

Evaluation of Noise Current From an Item of Station Apparatus

The total noise current from an item of energized equipment is determined by means of a single-phase laboratory test. The 60-cycle test-voltage and facility arrangement should be such that the electric field conditions found in the energized 3-phase station for the equipment in question are essentially duplicated in the laboratory test.

The value of the noise current on a spectral-density basis can be determined by using a radio-noise meter with a root-mean-square (rms) detector. Since this type of instrument is not in widespread use, the total noise current will be evaluated by a standard NEMA[5] Radio Influence Voltage (RIV) laboratory test on the equipment in question, using the standard quasi-peak instrument. This evaluation assumes that a ratio k_1 exists, which can be found by measurement, that will relate a quasi-peak noise-meter reading obtained from a NEMA test to one that would be obtained with an rms meter having the same

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bandwidth. The same problem of relating rms to quasi-peak values will also be encountered at the end of this analysis since quasi-peak instruments are commonly used both for RIV and RI field measurements. At that point in the analysis, a constant k_2 will be introduced which enables the results to be given on a quasi-peak basis and the two constants k_1 and k_2 will be assumed to be the same.

The spectral density of the total noise current entering phase A, in Fig. 1, will be:

$$SD\left[i_t\right] = \frac{(RIV)^2}{k_1^2 \, Z_{tc}^2 \, \Delta f} \qquad (1)$$

The impedance of the laboratory-test circuit, Z_{tc} would normally be equal to 150 ohms. Nomenclature is given after Appendix I.

Modal Current Distribution

A value of the spectral density of the noise current feeding into one phase of the 3-phase line has been determined. The next step in the analysis is to take this current and apportion it into the three natural propagation modes of the 3-phase (conductor) system, there being n modes for an n conductor system. The procedure for doing this has been outlined in a previous paper.[6] The details of this apportionment are given in Appendix I. The following developments are also included in Appendix I:

1. Determination of modal conductor voltages at the station.
2. Finding these voltages at a desired point of observation down the line.
3. At this longitudinal point of observation, determining the resultant electric field at a desired lateral point from the line, point X in Fig. 2.

Correlation Considerations

An important consideration of the analysis in Appendix I and other developments in this paper is the question of correlation between noise voltages, or currents, within modes, from different modes, and from different sources of generation. Generally, correlation between voltages implies that a knowable phase-relation exists between them. Noncorrelation would imply that the phase-relation is not knowable and this situation would arise when comparing voltages from two or more different sources of noise. Noncorrelation also arises in some degree when comparing voltages from different modes after propagation down a line has taken place. These correlation considerations have been discussed in a previous paper.[7] The analysis in this paper will assume the following:

1. Correlation within a mode exists for a single-source problem.
2. Correlation is lost between modes as pulses travel away from the station.
3. Noise voltages or currents from different sources are uncorrelated.

Radio Noise Level

From Appendix I, the following equation applies to the modal electric field at a point s down the line from the station and a lateral point x from the line:

$$SD\left[E_x^{(n)}\right] = \frac{6^{-2s\alpha^{(n)}}\left(\left|\zeta^{(n)}\right|\right)^2\left(\gamma_x^{(n)}\right)^2 SD\left[i_t\right]}{\left(N_a^{(n)}\right)^2\left(\lambda^{(n)}\right)^2} \quad (2)$$

With noncorrelation between modes, the total electric field at point x (location of observer) would be

$$SD\left[E_x\right] = \sum_{n=1}^{3} SD\left[E_x^{(n)}\right] \quad (3)$$

Assume, as discussed previously, that k_2 exists such that

$$(RI)^2 = k_2^2\,\Delta f\, SD\left[E_x\right] \quad (4)$$

and also that $k_1 = k_2$ (5)

Combining equations 1, 2, 3, 4, and 5, and taking the square root yields the following for the 3-conductor case:

$$RI = (RIV)\left(\frac{1}{Z_{tc}}\right)\left(\frac{6^{-2s\alpha^{(1)}}\left(\left|\zeta^{(1)}\right|\right)^2\left(\gamma_x^{(1)}\right)^2}{\left(N_a^{(1)}\right)^2\left(\lambda^{(1)}\right)^2} + \frac{6^{-2s\alpha^{(2)}}\left(\left|\zeta^{(2)}\right|\right)^2\left(\gamma_x^{(2)}\right)^2}{\left(N_a^{(2)}\right)^2\left(\lambda^{(2)}\right)^2} + \frac{6^{-2s\alpha^{(3)}}\left(\left|\zeta^{(3)}\right|\right)^2\left(\gamma_x^{(3)}\right)^2}{\left(N_a^{(3)}\right)^2\left(\lambda^{(3)}\right)^2}\right)^{1/2} \quad (6)$$

With equation 6 and line and station constants, the RI value at a distance x laterally from the line and a distance S from the station can be found if the RIV test value of the equipment is known.

Multiple Sources

The preceding analysis was made on the basis of a single source of corona. The addition of other sources, either on the same phase or on other phases, is made on an uncorrelated basis and, thus, their contributions to the total electric field at the point of observation are calculated separately and simply added as in equation 3. This would imply, for example, that two identical sources, both on the same outside phase, or one on each outside phase, would give a resultant RI field which would be 3 decibels (db) higher than the case of one source on one of the outside phases.

Illustrative Examples

A. One Source on One Outside Phase.

As an illustration of the use of equation 6, consider the following data for a horizontal, single conductor per phase, 3-phase, long line and station. For this example, the coupling between phases in the station was assumed to be negligible and wave traps were not present.

f = 1 megacycle

Z_{tc} = 150 ohms

$$[Z_s] = \begin{bmatrix} -j79.6 & 0 & 0 \\ 0 & -j79.6 & 0 \\ 0 & 0 & -j79.6 \end{bmatrix} \text{ ohms}$$

h = 46 feet

x = 139 feet from line center

r = 1.25 inches

s = 0.1 miles to 7 miles

phase spacing = 39 feet

and from the Project EHV computer program

$$[N] = \begin{array}{c} \quad (1) \quad\quad (2) \quad\quad (3) \\ \begin{bmatrix} +.458 & -.707 & +.538 \\ -.763 & 0 & +.647 \\ +.458 & +.707 & +.538 \end{bmatrix} \end{array}$$

and

$\alpha^{(1)}$ = .03025 nepers/mile

$\alpha^{(2)}$ = .1642 nepers/mile

$\alpha^{(3)}$ = .735 nepers/mile

and

$$\left.\begin{aligned}\lambda^{(1)} &= 5.653\\ \lambda^{(2)} &= 6.348\\ \lambda^{(3)} &= 8.350\end{aligned}\right\}$$ Modes are numbered in order of increasing eigenroot.

All of the above data was combined with the development in Appendix I and equation 6 to yield the lower curve in Fig. 3, which gives the ratio of RI/RIV for distances along the line up to 7 miles. As an example of the use of this curve, assume that the corona-producing device on an outside phase in the station has an RIV test voltage of 2,000 microvolts (μv). The RI level at a distance of 1 mile from the station and at the 139-foot lateral point as a result of the station generation on the outside phase would be

From Fig. 3 (lower curve)

$$RI/RIV = 1.2 \times 10^{-3} \text{ meters}^{-1} \tag{7}$$

therefore

$$RI = (1.2 \times 10^{-3})(2000) = 2.4 \text{ μv/meter} \tag{8}$$

B. One Source on Each of Three Phases.

For this example, it was assumed that in the station three identical sources exist (one on each phase) with the same line data as for Example A. The calculation procedure here is to compute the value of SD $\left[E_x^{(n)}\right]$, n = 1, 2, and 3, for a noise generator on the center phase only. These values are added with twice those obtained from Example A, since the two outside phases are symmetrical. The procedure for calculating the RI/RIV ratio would then be the same as outlined in equations 1 through 6. The results of this calculation are given in the upper curve in Fig. 3.

It is interesting to note the per cent distribution of SD $\left[E_x^{(n)}\right]$ with respect to the total value as distance from the station is increased. This is plotted in Fig. 4, for Example B. These curves show that the line-to-ground mode predominates at the start for about one mile and declines rapidly. Mode 2 reaches a maximum at s ≈ 3 miles and then declines. Mode 1 rises almost linearly, initially, and eventually predominates because of its low attenuation rate. These distribution curves are, of course, dependent on the lateral distance from the center of the line.

The illustrative examples given yield answers for the specific cases only. They are not intended as generalizations, but are intended to illustrate the calculation procedure. These results would be modified by changes in modal attenuation values, line geometry, station impedances (self and mutual), and other quantities treated in the analysis.

CONCLUSIONS

1. A method has been presented for calculating the effect of single or multiple sources of station radio-noise on the transmission-line noise level.

2. Two illustrative examples are given; to show the results of noise on one phase only, and on all three phases in a station.

3. For the example shown, the influence of mode 3 (line-to-ground) predominates close to the station, while at distances greater than approximately 1 mile the line-to-line modes predominate for the 139-foot lateral point.

4. The techniques presented are applicable to calculate the effects on transmission-line RI levels of corona from line hardware, regularly or irregularly spaced along the line.

APPENDIX I

Phase Voltages

As seen in Fig. 1, noise current is injected into one phase, and the resultant phase voltages are obtained from the following development. A phasor voltage and current argument is used since correlation is present.

$$[I_t] = [I_L] + [I_s] \tag{9}$$

and

$$[I_L] = [Z_L]^{-1} [V] \tag{10}$$

and

$$[I_s] = [Z_s]^{-1} [V] \tag{11}$$

therefore

$$[I_t] = \left[[Z_L]^{-1} + [Z_s]^{-1}\right] [V] \tag{12}$$

and

$$[V] = \left[[Z_L]^{-1} + [Z_s]^{-1}\right]^{-1} [I_t] \tag{13}$$

The elements of the line-impedance matrix $[Z_L]$ are

$$Z_{ii} = 60 \ln \left(\frac{2h}{r}\right) \quad i = 1, 2, 3 \tag{14}$$

$$Z_{ij} = 60 \ln \left(\frac{R_{ij'}}{R_{ij}}\right) \quad \begin{matrix} i = 1, 2, 3 \\ j = 1, 2, 3 \\ i \neq j \end{matrix} \tag{15}$$

The elements of the station-impedance matrix $[Z_s]$ will, in general, contain both self and mutual terms.

The voltage and current matrices in equation 14, written out, would be

$$[V] = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{16}$$

$$[I_t] = \begin{bmatrix} i_t \\ 0 \\ 0 \end{bmatrix} \tag{17}$$

As indicated in the section on Multiple Sources, the analysis for sources on all three phases will always be carried out on a one-source-at-a-time basis; hence, the current column matrix will contain only one nonzero element.

Modal Voltages

The next step in the analysis is to transform the phase voltages into modal-phase voltages. The phasor argument is continued since correlation is present. It has been shown[6] that a transformation matrix [M] exists such that modal voltages and phase voltages are related as follows:

$$[V^{(n)}] = [M][V] \tag{18}$$

let us now define an [N] matrix such that

$$[N] = [M]^{-1} \tag{19}$$

and therefore

$$[V] = [N][V^{(n)}] \tag{20}$$

equation 20, written out, would be

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} N_a^{(1)} & N_a^{(2)} & N_a^{(3)} \\ N_b^{(1)} & N_b^{(2)} & N_b^{(3)} \\ N_c^{(1)} & N_c^{(2)} & N_c^{(3)} \end{bmatrix} \begin{bmatrix} v_a^{(1)} \\ v_a^{(2)} \\ v_a^{(3)} \end{bmatrix} \tag{21}$$

The elements of the [N] matrix are derived from an eigenvector analysis of the conductor system. Three properties of the set of [N] matrix elements are

$$N_a^{(n)} = \Delta^{(n)} \frac{v_a^{(n)}}{v_c^{(n)}}$$

$$N_b^{(n)} = \Delta^{(n)} \frac{v_b^{(n)}}{v_c^{(n)}}$$

$$N_c^{(n)} = \Delta^{(n)} \tag{22}$$

and

$$1 = \left(N_a^{(n)}\right)^2 + \left(N_b^{(n)}\right)^2 + \left(N_c^{(n)}\right)^2 \tag{23}$$

and

$$[N] = [M]' \tag{24}$$

Computer programs are available for computing the elements of the [N] matrix for 1- or 2-circuit, 3-phase lines with a maximum of 2 ground wires and 4 conductors per bundle.

Matrix equation 18 can be transformed by means of equations 19, 21, and 24 to

$$\begin{bmatrix} v_a^{(1)} \\ v_a^{(2)} \\ v_a^{(3)} \end{bmatrix} = \begin{bmatrix} N_a^{(1)} & N_b^{(1)} & N_c^{(1)} \\ N_a^{(2)} & N_b^{(2)} & N_c^{(2)} \\ N_a^{(3)} & N_b^{(3)} & N_c^{(3)} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{25}$$

It is convenient from a notational standpoint to summarize the results of the development shown in equations 9 through 25 for obtaining modal voltages from injected current as follows:

$$v_a^{(n)} = \xi^{(n)} i_t \tag{26}$$

where $\xi^{(n)}$ is a transfer function obtainable from equations 9 through 25 and dependent on line geometry, station impedance, and the phase where noise current is injected.

At this point, the phasor-voltage argument presented in equation 26 is transformed to a spectral-density argument with

$$SD\left[v_a^{(n)}\right] = \left(\left|\xi^{(n)}\right|\right)^2 SD\left[i_t\right] \tag{27}$$

At a distance s from the station, and with regard to attenuation, the modal voltage on phase A would be

$$SD\left[v_a^{(n)}\right]_s = \epsilon^{-2s\alpha^{(n)}} \left(\left|\xi^{(n)}\right|\right)^2 SD\left[i_t\right] \tag{28}$$

Electric Field Intensities

To see how, for a single mode, electric field values are obtained, consider Fig. 2. Now, if the electric field at point x is desired, the following steps are made

$$[V] = [A][Q] \tag{29}$$

and

$$[Q] = [A]^{-1}[V] \tag{30}$$

Once the lineal charge density for each phase conductor is known, the contributions to E_x can be obtained and summed to get the total field

$$E_x = \frac{Q_a\, 2h_a}{2\pi\epsilon_o\left(h_a^2 + (x-\ell_a)^2\right)} + \frac{Q_b\, 2h_b}{2\pi\epsilon_o\left(h_b^2 + (x-\ell_b)^2\right)} + \frac{Q_c\, 2h_c}{2\pi\epsilon_o\left(h_c^2 + (x-\ell_c)^2\right)} \tag{31}$$

Now, if v_a, v_b, and v_c are modal quantities, then

$$E_x^{(n)} = \frac{1}{\lambda^{(n)}}\left[\frac{v_a^{(n)}\, 2h_a}{h_a^2 + (x-\ell_a)^2} + \frac{v_b^{(n)}\, 2h_b}{h_b^2 + (x-\ell_b)^2} + \frac{v_c^{(n)}\, 2h_c}{h_c^2 + (x-\ell_c)^2}\right] \tag{32}$$

and if $v_a^{(n)}$ is known

$$\text{then } v_b^{(n)} = v_a^{(n)}\left(\frac{N_b^{(n)}}{N_a^{(n)}}\right) \text{ and } v_c^{(n)} = v_a^{(n)}\left(\frac{N_c^{(n)}}{N_a^{(n)}}\right) \tag{33}$$

substituting 33 into 32, and rearranging

$$E_x^{(n)} = \frac{v_a^{(n)}}{N_a^{(n)}\lambda^{(n)}}\left[\frac{N_a^{(n)}\, 2h_a}{h_a^2 + (x-\ell_a)^2} + \frac{N_b^{(n)}\, 2h_b}{h_b^2 + (x-\ell_b)^2} + \frac{N_c^{(n)}\, 2h_c}{h_c^2 + (x-\ell_c)^2}\right] \tag{34}$$

Thus, for a pure modal system, only the modal voltage on one phase is required to determine the total field produced by single-mode charges on all three conductors.

Equation 34 on a spectral-density basis would be

$$SD\left[E_x^{(n)}\right] = \frac{SD\left[v_a^{(n)}\right]\left(\gamma_x^{(n)}\right)^2}{\left(N_a^{(n)}\right)^2\left(\lambda^{(n)}\right)^2} \qquad (35)$$

where $\gamma_x^{(n)} = \left[\frac{N_a^{(n)}\,2h_a}{h_a^2 + (x-\ell_a)^2} + \frac{N_b^{(n)}\,2h_b}{h_b^2 + (x-\ell_b)^2} + \frac{N_c^{(n)}\,2h_c}{h_c^2 + (x-\ell_c)^2}\right]$

substituting equation 28 into 35 yields

$$SD\left[E_x^{(n)}\right] = \frac{\epsilon^{-2s\alpha^{(n)}}\left(\left|\zeta^{(n)}\right|\right)^2\left(\gamma_x^{(n)}\right)^2 SD\left[i_t\right]}{\left(N_a^{(n)}\right)^2\left(\lambda^{(n)}\right)^2} \qquad (36)$$

NOMENCLATURE

- $SD[\ ]$ = spectral density of
- k = empirical constant
- Z_{tc} = laboratory-test circuit impedance
- $[I]$ = phase-current matrix
- $[Z]$ = impedance matrix
- $[V]$ = phase-voltage matrix
- $[V^{(n)}]$ = modal-voltage matrix
- f = frequency
- Δf = bandwidth
- (n) = modal-number superscript
- s = longitudinal distance from station to point of observation
- x = lateral distance to point of observation
- h = conductor height

- R_{ij} = distance between conductor i and j
- $R_{ij'}$ = distance between actual conductor i and image conductor j
- r = conductor radius
- ℓ = horizontal distance to axis
- v = phasor voltage
- i = phasor current
- E = electric-field intensity
- $[M]$ = modal-transformation matrix
- $[N]$ = inverse of $[M]$
- $\alpha^{(n)}$ = attenuation constant for mode n
- $\gamma_x^{(n)}$ = normalized-field factor at point x for mode n
- $\lambda^{(n)}$ = eigenroot for mode n
- A = potential coefficient
- Q = lineal-charge density
- $\Delta^{(n)}$ = modal-normalizing constant
- $\zeta^{(n)}$ = transfer function

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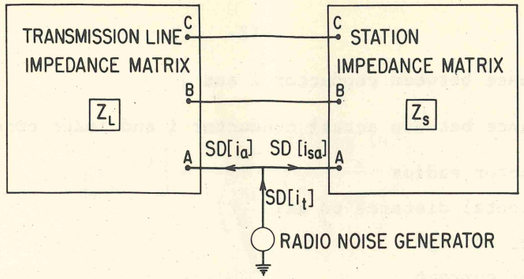

Fig. 1. Line and station impedance matrices and constant-current radio-noise generator.

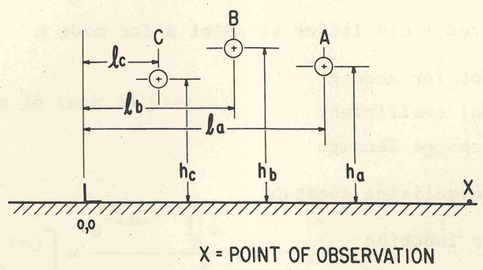

Fig. 2. Three-phase line.

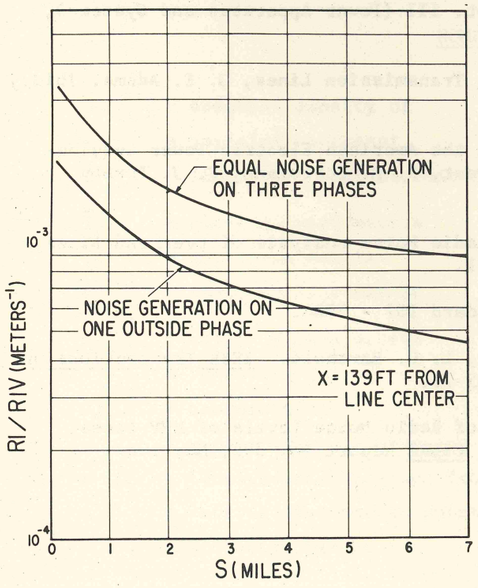

Fig. 3. RI/RIV ratios vs. distance from station.

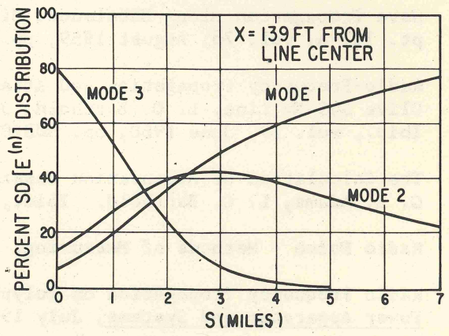

Fig. 4. Per cent modal distribution of SD $\left[E_x\right]$.